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Acoustic Transmission Loss and Pulse Time-Spread Measured Off the South Carolina Coast During the 1997 Littoral Warfare Advanced Development System Concept Validation Experiment

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13. ABSTRACT (Maximum 200 words)

Acoustic transmission loss and pulse time-spread measurements were performed off the South Carolina coast as part of the Littoral Warfare Advanced Development (LWAD) environmental measurement support provided for the 1997 System Concept Validation (SCV 97) experiment. Although the extensive acoustic propagation survey originally planned for this experiment was canceled due to hardware failure, high-quality acoustic transmission loss data at three ranges (2, 3, and 4 nm) were collected aboard the R/V Gosport at two sites using the LWAD echo repeater F-56 acoustic projector and drifting AN/SSQ-57A sonobuoys. High-quality transmission loss and time-spread data were also provided by the SQW-53C LFM signal (300 ms duration, 200 Hz bandwidth) generated by U.S.S. Nicholson as it made a straight-line run to acoustic receivers deployed from the R/V Gosport. These data produce transmission loss values of 80 to 90 dB at a 4 nm range, which agree well with measurements made near this general site in LWAD FTE 96-2, but are 10 dB greater than predicted by several modeling efforts before the LWAD FTE 96-2 and SCV 97 experiments. Analysis of the SQS-53C data shows significant time-spread and a strong multipath acoustic propagation environment.

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1.   INTRODUCTION

Proper evaluation of underwater acoustic system performance requires a knowledge of the signal propagation environment. The complex geo-acoustic and oceanographic environment found in the littoral waters of the world's oceans make determination of the signal propagation environment particularly important. Consequently, the Littoral Warfare Advanced Development (LWAD) program provides a range of environmental measurements intended to define the acoustic propagation environment. These measurements include oceanographic properties, geo-acoustic properties, reverberation, and acoustic propagation. This report describes acoustic propagation measurements made in support of the bistatic Air-Deployed Low Frequency Sonar (ALFS)-AN/SQS53C Interoperability Testing performed during the LWAD System Concept Validation (SCV) experiment in September of 1997.
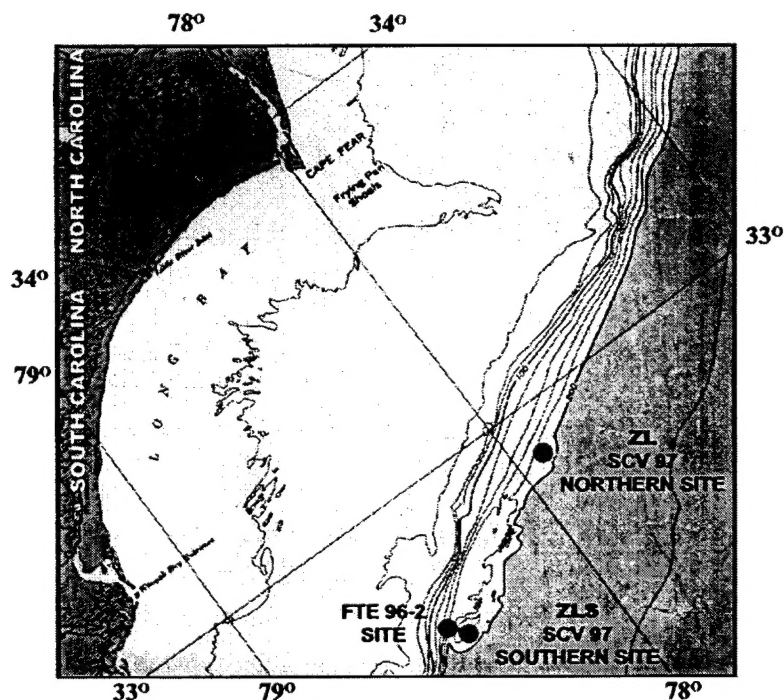

Figure 1: Chart of the SCV 97 experiment site off the coast of South Carolina. Acoustic propagation measurements were made at sites ZL and ZLS in water 180 to 190 m deep. In addition, the FTE 96-2 experiment site where transmission loss data were also collected is shown.

The SCV 97 experiment was performed off the coast of South Carolina in the Long Bay area from September 6 to September 15, 1997. The experiment is described in detail in the SCV 97 Test Plan [1] and the SCV 97 Quick Look Proceedings [2]. The experiment sites are shown in Figure 1. The bottom at sites ZL and ZLS consisted primarily of exposed limestone. Detailed geo-acoustic and oceanographic properties of the area are described in previous LWAD Reports [2, 3, 4, 5]. This area was also the site of the second LWAD

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Focused Technology Experiment performed in 1996 (FTE 96-2) in which transmission loss data were also collected [6].

Two ships were involved in the planned transmission loss (TL) measurements: The R/V Acoustic Pioneer was scheduled to act as a source ship and the R/V Gosport was scheduled to deploy the NRL 32 element acoustic Vertical Line Array (VLA) and AN/SSQ-57A sonobuoys as receivers. The test plan scheduled 20 hours of transmission loss data collection at site ZL, however failure of equipment supporting the TL projector system aboard the R/V Acoustic Pioneer prevented the planned TL runs from occurring. While the R/V Acoustic Pioneer put into port for repairs, the R/V Gosport collected simple acoustic propagation data using AN/SSQ-57A sonobuoys tethered from the ship's rigid hull inflatable boat (RHIB) and the LWAD Echo Repeater USRD F-56 acoustic projector. CW and broadband data were collected at source-receiver ranges of 2, 3, and 4 nm (4 nm was the limit of the sonobuoy RF telemetry). During environmental data collection at site ZL it was noted that unusually high ocean currents were present due to intrusion of the Gulf Stream. These high currents represented an unacceptable operational environment for the primary SCV 97 test participants, so a second site which did not exhibit these high currents, identified as site ZLS, was found in the southwest corner of the operational area. Again, the R/V Gosport collected simple acoustic propagation data at ranges of 2, 3, and 4 nm using AN/SSQ-57A sonobuoys and the LWAD Echo Repeater acoustic projector. The R/V Gosport RHIB could not be used at this site due to prevailing sea conditions. Acoustic propagation data over a range of 3 to 7 nm were also collected at site ZLS using a 16 element acoustic VLA and drifting sonobuoys deployed from the R/V Gosport and the SQS-53C SONAR projector aboard the U.S.S. Nicholson. Additional acoustic propagation data were collected at site ZLS by recording the transmissions of the ALFS system during experiment events 11 and 12 on the acoustic VLA and sonobuoy receivers deployed from the R/V Gosport.

This report presents results from data processing of the CW propagation data from site ZL and the broadband SQS-53C propagation data from site ZLS. The latter data set was selected by the participating projects as their highest priority for supporting their performance prediction analyses.

2.   SITE ZL TRANSMISSION LOSS MEASUREMENTS

Acoustic propagation measurements were made at site ZL using an acoustic projector deployed from the R/V Gosport and drifting sonobuoy receivers. The measurement configuration is shown in Figure 2. Two AN/SSQ-57A sonobuoys were tethered to the R/V Gosport RHIB. One sonobuoy was set to deploy a hydrophone at a 60 ft depth and the second sonobuoy was set to deploy a hydrophone at a 400 ft depth, however both hydrophones deployed at the 400 ft depth (water depth was approximately 590 ft). GPS position of the RHIB was recorded every 15 minutes during the propagation measurements. The RHIB's range to the R/V Gosport was also determined by ship's RADAR. The R/V Gosport positioned itself at ranges of 2, 3, and 4 nm from the RHIB (4

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nm was the limit of the useful sonobuoy RF telemetry range) along the 180 meter isobath and deployed the LWAD echo repeater F-56 projector at a depth of 50 ft (some 200 ft depth data were also collected at a range of 2 nm). Both the R/V Gosport and RHIB were drifting during acoustic propagation measurements.
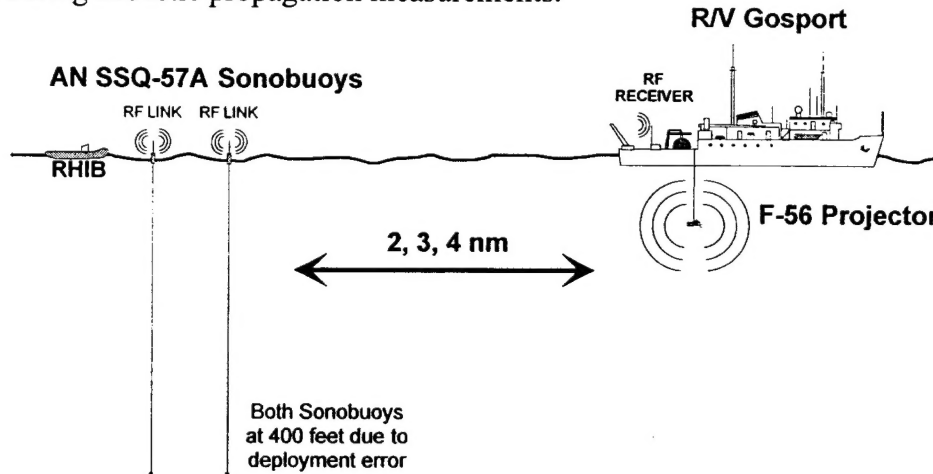

Figure 2: Measurement configuration for the acoustic propagation measurements performed at sites ZL and ZLS.

Figure 3 shows the equipment configuration of the LWAD echo repeater system as used in acoustic propagation measurements. Acoustic waveforms were generated in the R/V Gosport laboratory and cabled to the Echo Repeater Van. These waveforms were recorded coherently on the same data recorders used to record the acoustic receiver data. A personal computer equipped with a digital-to-analog conversion board was used to generate a continuous three tone CW comb with equal amplitude frequencies of 2.240, 3.504, and 4.750 kHz. An HP 8904 Function Synthesizer was used to generate a 2.5 s duration, 500 Hz bandwidth up-swept LFM with starting frequencies of 2.0, 3.0, and 3.5
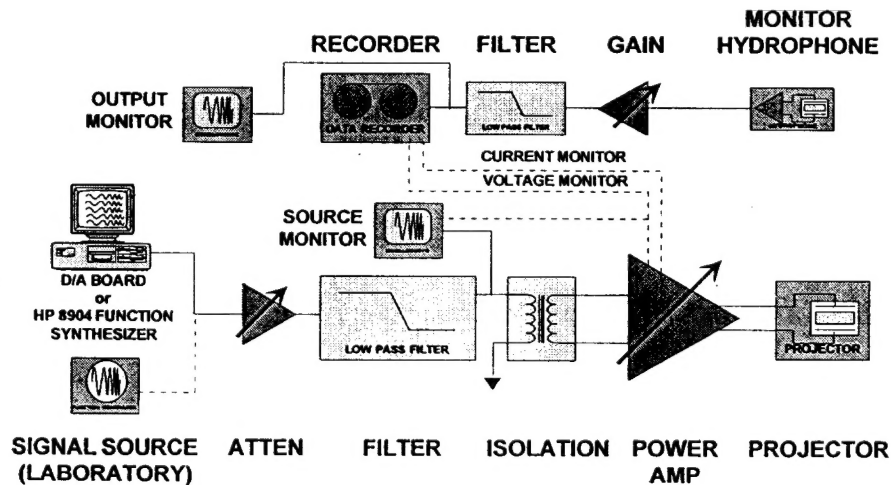

Figure 3: Equipment configuration for the LWAD echo repeater system as used for acoustic propagation measurements.

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kHz. A 2.5 s delay between pulses was used for this waveform.. The Transmission Voltage Response curve (TVR) of the USRD F-56 transducer is shown in Figure 4 (a more complete characterization of this projector can be found in the Echo Repeater Test Report [8]). The F-56 projector TVR shows a nearly linear 6 dB per kHz frequency response in the 2 to 5 kHz band which must be considered in calibrating the transmission
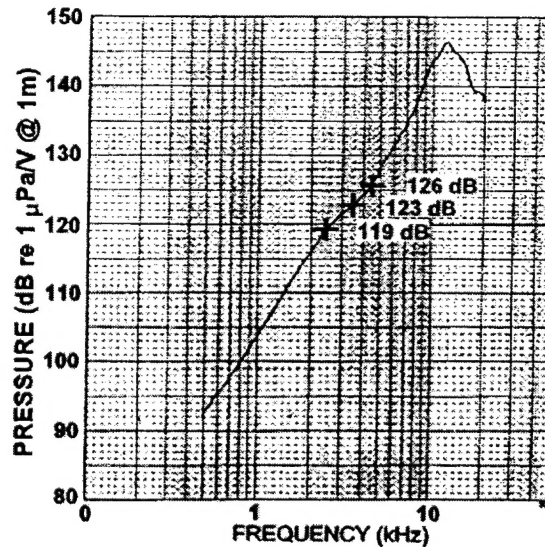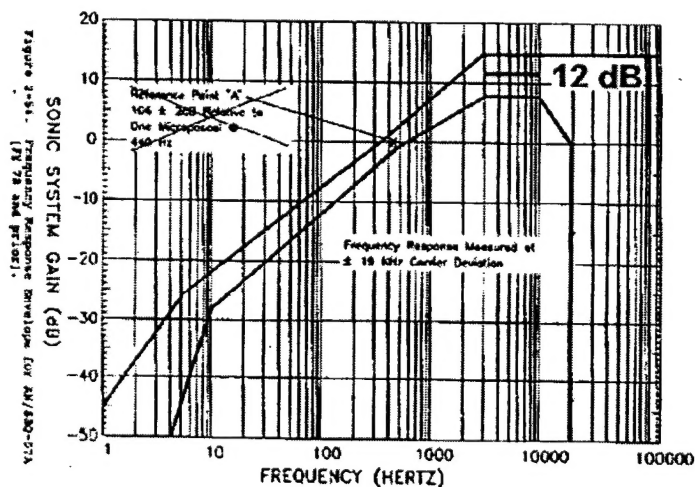

Figure 4: Transmitting Voltage Response curve for USRD F-56 acoustic projector used in transmission loss measurements at sites ZL and ZLS.

SONOBUOY FREQUENCY RESPONSE CURVE

Figure 5: Calibration curve for AN/SSQ-57A sonobuoy used in acoustic propagation measurements at Sites ZL and ZLS. This curve shows the sonobuoy frequency response relative to 106 dB re 1 µPa/0.5 V at 440 Hz. The sensitivity at 3500 Hz is given by -106 - 6 + 12 = -100 dB re 1 V/µPa.

loss data. For the acoustic propagation data collected at site ZL, the F-56 source level at 3500 Hz was 169 dB re 1 μPa @ 1m as determined by both the calibrated monitor hydrophone and the TVR curve.

The AN/SSQ-57A sonobuoy frequency response curve is shown in Figure 5. From 3 to 10 kHz the frequency response (including the frequency-to-voltage demodulation of the sonobuoy receiver, which is not shown here) is essentially flat with a hydrophone sensitivity of -100 dB re 1 V/μPa. At 2000 Hz the sensitivity drops to -98 dB re 1 V/μPa.

2.1. SITE ZL TRANSMISSION LOSS

Acoustic propagation data were collected at site ZL on September 9, 1997 between the hours of 1830 to 2100 (Z). Figure 6 shows a set of sound speed profiles collected during this period. The sound speed profile shows a surface mixed layer with near iso-velocity characteristics to a depth of 60 m (197 ft). Below the mixed layer the sound speed profile is downwardly refracting. This unusually deep mixed layer may be due to the intrusion of Gulf Stream water driven by Hurricane Erika. Water depth at this site was approximately 180 m (590 ft).
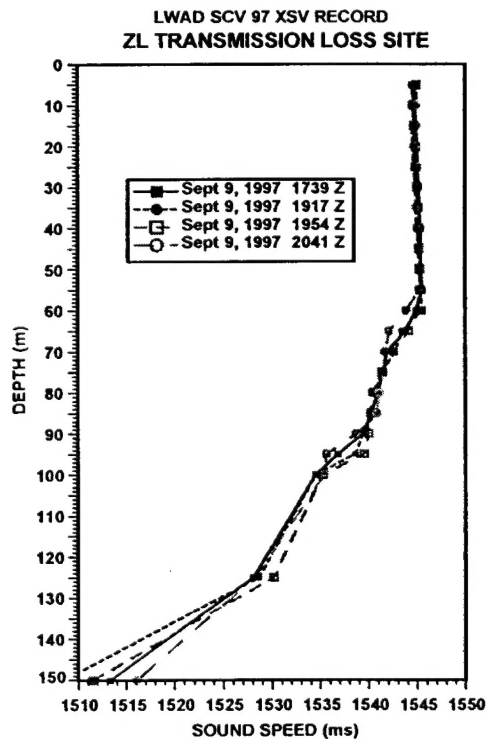

LWAD SCV 97 XSV RECORD
ZL TRANSMISSION LOSS SITE

Sept 9, 1997 1739 Z
Sept 9, 1997 1917 Z
Sept 9, 1997 1954 Z
Sept 9, 1997 2041 Z

Figure 6: Sound speed profiles collected at site ZL during transmission loss measurements.

Representative raw spectrum analyzer plots of the 3-tone, equal amplitude, CW comb signal (as recorded on the SONY data recorder) at ranges of 2, 3.3, and 4 nm are shown in Figure 7. The spectrum has not been corrected for the frequency response of the sonobuoy receiver, however the reader should note that the sonobuoy frequency response

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is flat from 3 kHz to 10 kHz and only 2 dB down at 2 kHz (see Figure 5). The high frequency rolloff is the result of the 5 kHz bandwidth of the SONY data recorder. Transmission loss was calculated from these spectrum analyzer measurements using the F-56 source level, corrected for the projector frequency response (see Figure 4), and sonobuoy frequency dependent sensitivity (see Figure 5). These transmission loss results are presented in Table 1.
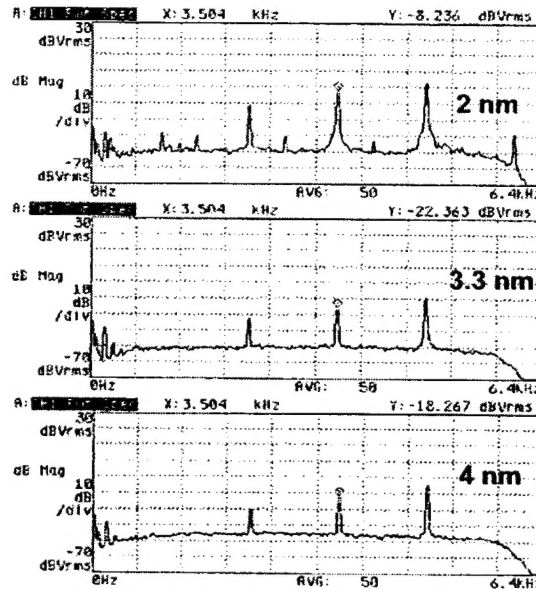

Figure 7: Raw Spectrum Analyzer display of the 3 tone CW comb signal as seen by a sonobuoy at ranges of 2, 3.3, and 4 nm. The units are dB$_{VRMS}$ (see Figure 5 for sonobuoy calibration curve).

RANGE	FREQUENCY		
	2,240 Hz	3,504 Hz	4,750 Hz
2 nm	77 dB	69 dB	70 dB
3.3 nm	87 dB	83 dB	82 dB
4 nm	85 dB	79 dB	78 dB

Table 1: CW Transmission loss measured at site ZL for ranges of 2, 3.3, and 4 nm. Source depth was 15.2 m (50 ft) and receiver depth was 122 m (400 ft). Water depth was 180 m (590 ft).

These transmission loss values agree well at 3500 Hz with the CW transmission loss results presented in the LWAD FTE 96-2 transmission loss report [6] and with the SUS based (impulsive) transmission loss results of the Airborne Environmental Measurements (HEP) data collected by NAWC AD during the SCV 97 experiment [2]. Modeling efforts prior to SCV 97 [3] and as part of the FTE 96-2 transmission loss report [6] predicted CW transmission loss values 5 to 10 dB less at 3,500 Hz (for similar source-receiver configuration).

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2.2. SITE ZL AMBIENT NOISE

Figure 8 shows a representative ambient noise spectrum as seen on an AN/SSQ-57A sonobuoy deployed to a depth of 400 ft. The spectrum was calibrated at 3500 Hz, however the frequency response of the sonobuoy has not been applied (see Figure 5 for the sonobuoy frequency response). This spectrum was produced during the propagation measurements at site ZL while the R/V Gosport drifted at a range of 2 nm from the receiver (therefore near-ship noise contamination should be small). Since sea and wind conditions were very calm during these measurements, low ambient noise values would be expected. At 3,500 Hz the ambient noise was approximately 38 dB re 1 $\mu Pa/\sqrt{Hz}$. This value agrees well with values found in the literature [7].
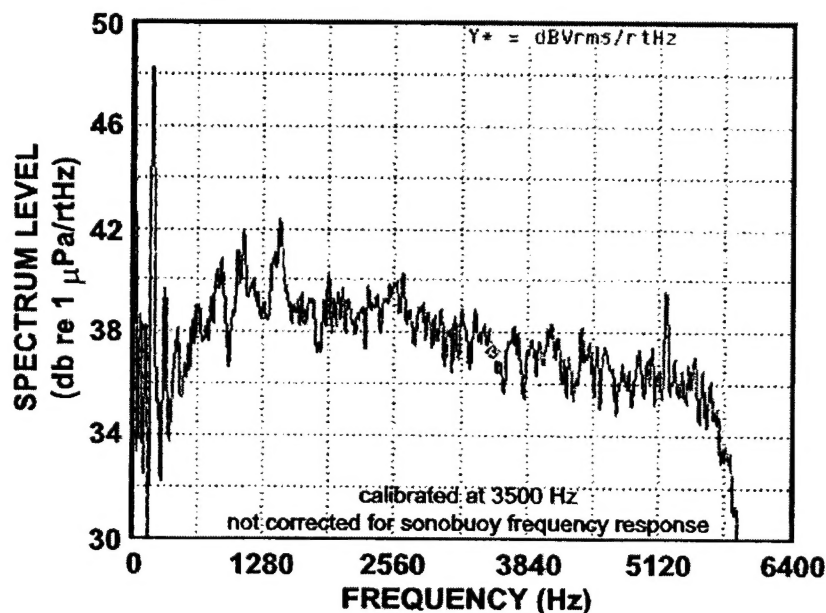

Figure 8: Site ZL ambient noise Spectrum Level as measured from a SSQ-57A sonobuoy at 400 ft depth. Spectrum Level was calibrated at 3500 Hz and has not been corrected for the sonobuoy frequency response (see Figure 5). Sonobuoy was deployed 2 nm from the R/V Gosport.

3. SITE ZLS SQS-53C RECEIVED PULSE ENERGY LEVEL and TIME-SPREAD MEASUREMENTS

Broadband acoustic propagation data were collected at site ZLS using the U.S.S. Nicholson SQS-53C SONAR as a source and the 16 element VLA and sonobuoys as receivers. The measurement configuration is shown in Figure 9. The drifting R/V Gosport deployed the 16-element acoustic VLA and two tethered AN/SSQ-57A sonobuoys as acoustic receivers. The VLA was deployed to a depth of 60 m (197 ft). One sonobuoy hydrophone was deployed at 18 m (60 ft), the second sonobuoy hydrophone was deployed at 122 m (400 ft). The water depth at this site was approximately 185 m

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(606 ft). Acoustic data were collected as the U.S.S. Nicholson made a direct run along the isobath to the R/V Gosport from a range of 7 nm to 3 nm. GPS position data were recorded every minute on both the R/V Gosport and U.S.S. Nicholson. These navigation data are plotted in Figure 10.
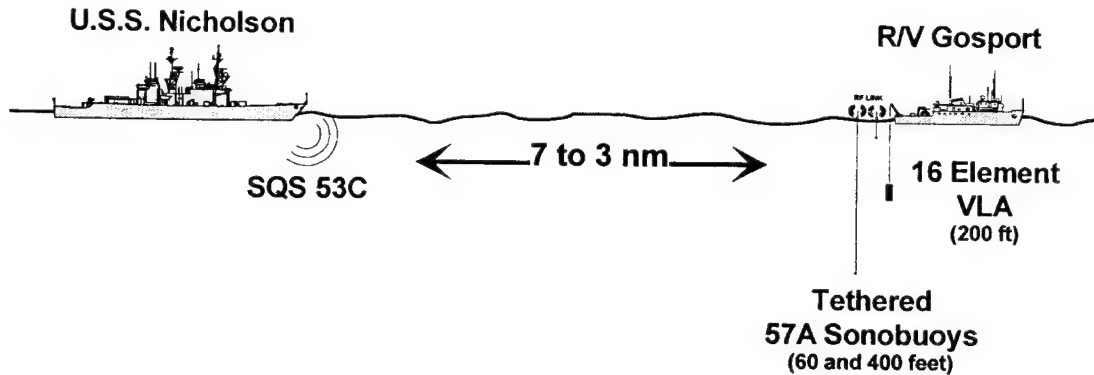

Figure 9: Measurement configuration for the SQS-53C acoustic propagation measurements at Site ZLS.
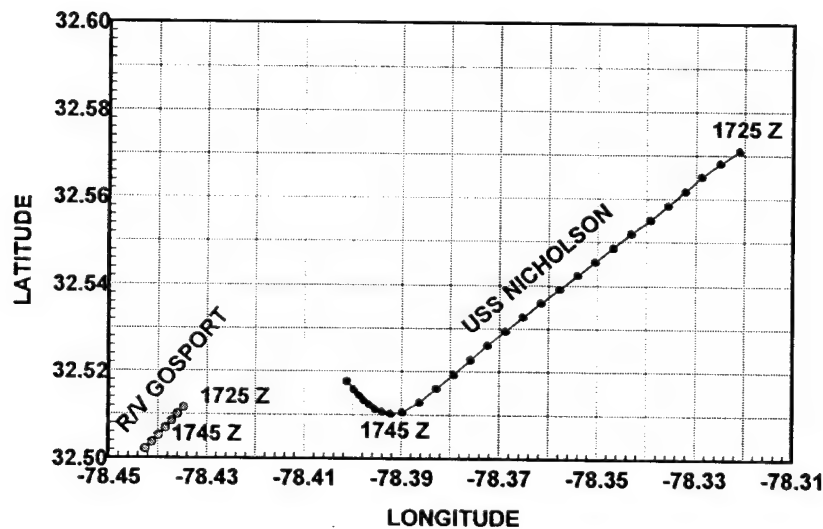

Figure 10: GPS navigation for R/V Gosport and U.S.S. Nicholson during acoustic propagation measurements at site ZLS on September 14, 1997.

The waveform projected by the U.S.S. Nicholson SQS-53C SONAR during the acoustic propagation run was a 200 Hz bandwidth (3263 to 3463 Hz), 300 ms duration, upswept LFM. The LFM pulse was transmitted every 13.835 s. Figure 11 shows a spectrum analyzer plot of this waveform as seen on the shallow (60 ft) and deep (400 ft) sonobuoy receivers. Peak averaging over 5 LFM pulses was used to generate this plot. The U.S.S. Nicholson was at a range of 6.8 nm. Received levels are similar for both the deep and shallow receivers, although there is some evidence of depth-dependent multipath

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structure (as expected). Note that the background noise level for the SQS-53C propagation data is approximately 50 dB re 1 $\mu Pa / \sqrt{Hz}$ at 5 kHz for both the deep and shallow sonobuoys (subtract 18 dB to convert from μPa to $\mu Pa / \sqrt{Hz}$). This 12 dB increase over ambient noise level is due to the R/V Gosport own-ship noise.
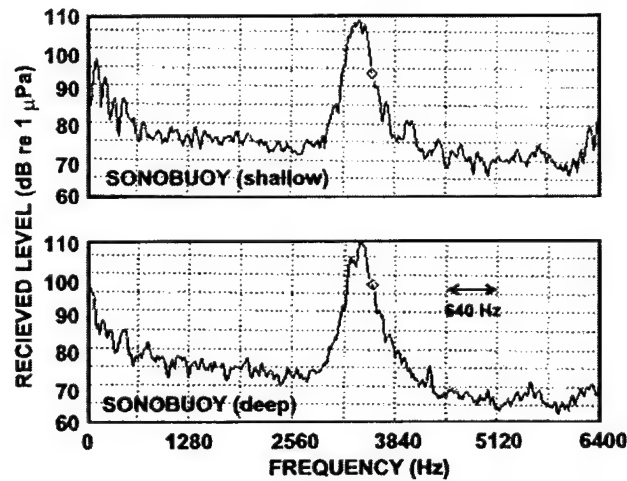

Figure 11: Spectrum analyzer plots of the SQS-53C waveform as seen on two tethered sonobuoys. Received level has been calibrated at 3,500 Hz and has not been corrected for the sonobuoy frequency response. Shallow sonobuoy is deployed at 60 ft, deep sonobuoy is deployed at 400 ft.
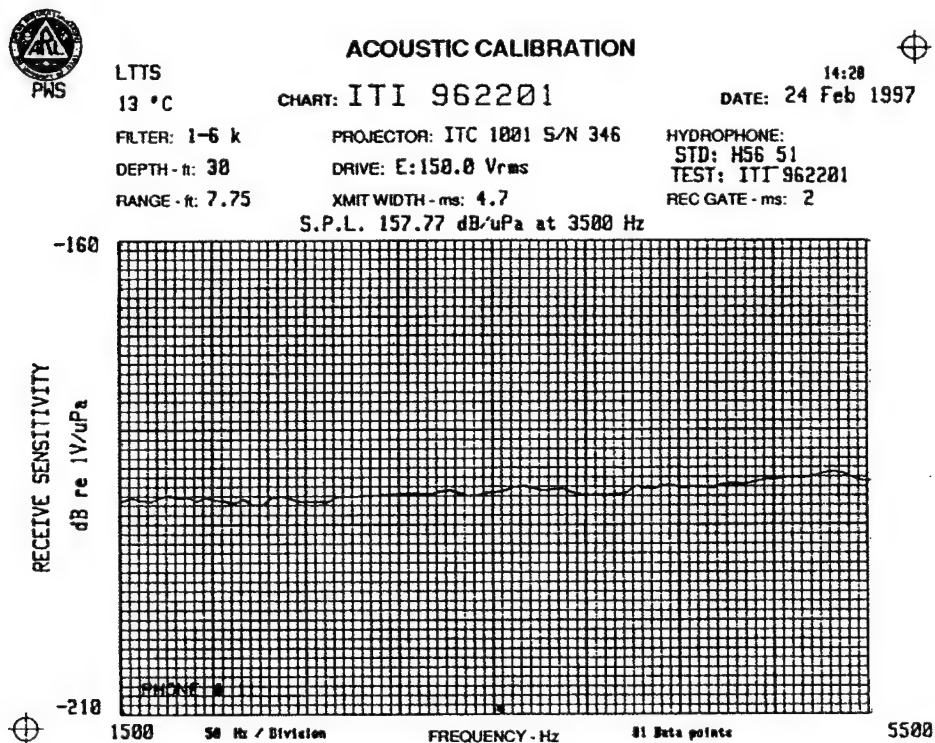

Figure 12: Hydrophone frequency response for channel 1 of the ITI array.

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The 16-element VLA was used to collect acoustic data during the SQS-53C propagation run. This array has two 8-element apertures. The first aperture is spaced at 21 cm and the second aperture is spaced at 4 cm. The signals from the 16 VLA hydrophones were low-pass filtered at 6 kHz and additional gain of 10 to 30 dB was applied before the signals were recorded. This report presents SQS-53C propagation results from acoustic data collected on channel 1 of the VLA. The channel 1 frequency response is shown in Figure 12 where it can be seen that the hydrophone sensitivity is relatively flat over the 2 to 4 kHz frequency band, with a value of -187 dB re 1 V/μPa.

Sound speed profiles collected at site ZLS during acoustic propagation measurements are presented in Figure 13. The mixed layer at site ZLS extends to a depth of 30 m. This is roughly half as thick as the mixed layer at site ZL, supporting the contention that the 60 meter mixed layer at site ZL was due to the Gulf Stream intrusion into the area.
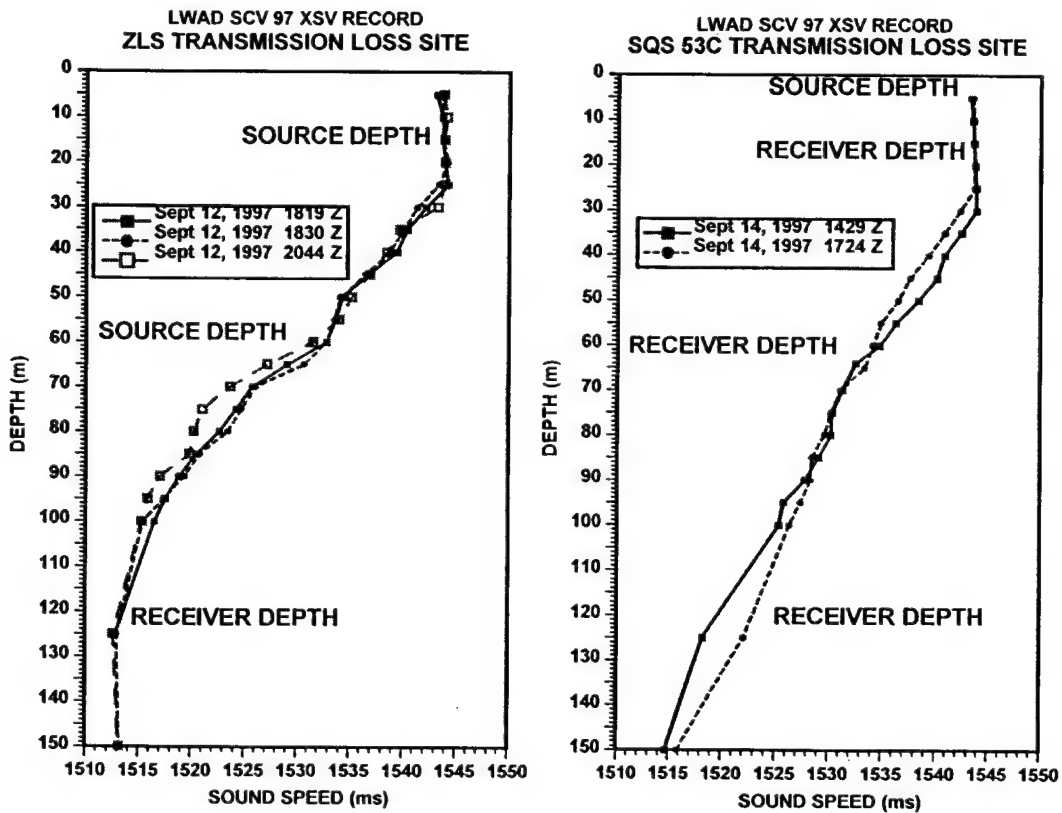

Figure 13: Sound speed profile collected at site ZLS acoustic propagation measurements. SQS-53C propagation measurements occurred between 1725 and 1750 (Z) on Sept 14, 1997.

3.1.   RECEIVED ENERGY LEVEL MEASUREMENTS

Matched filter (i.e. replica correlation) processing was applied to data received on VLA channel 1 over the time 1725 to 1752 hours (Z), 14 September 1997. The LFM replica used in the matched filter processing was generated from the equation:

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$$s(t) = e^{2\pi i[(F_c - \frac{BW}{2})t + \frac{BW}{2T}t^2]}$$

where F_c = 3363 Hz, BW = 200 Hz, and T=0.300 s. Note that the replica has not been corrected for the 30 Hz Doppler shift expected from the U.S.S. Nicholson traveling at 13 knots. Matched filter processing as applied to LWAD transmission loss data is described in the FTE 96-1 transmission loss report [9]. In the frequency domain, the matched filter power is given by:

$$\left|\hat{R}(\omega)\right|^2 = \frac{\left|S^*(\omega)\, R(\omega)\right|^2}{\left|S(\omega)\right|^2}$$

where $\hat{R}(\omega)$ is the matched filter output, $R(\omega)$ is the VLA channel 1 voltage spectrum, and $S(\omega)$ is the replica signal spectrum. The received energy level is calculated by integrating the frequency domain matched filter power over the processing band and then converting to dB. The hydrophone sensitivity and gain factors are then applied:

$$E_R = P_D - H_{ens} - G_o + 10 \log (T)$$

where E_R is the received energy level in dB re 1 μPa^2 s, P_D is the matched filter power in dB_{VRMS}, H_{ens} is the hydrophone sensitivity, G_o is the system gain, and T is the replica duration in s.

The transmission loss can be calculated by subtracting the transmitted pulse energy level from the received pulse energy level:

$$TL = E_R - E_S$$

The received pulse energy level for the SQS-53C propagation run as a function of time and range is shown in Figure 14. LFM pulses were transmitted every 13.835 s. At a transit speed of 13 knots this time interval corresponds to an approximate 93 m range interval. Received pulse energy level varies from 125 dB re 1 μPa^2 s at 6.8 nm to 155 dB re 1 μPa^2 s at 2.5 nm. Note that the received pulse energy level plot can be divided into three characteristic regions. The first region covers the time interval 0 to 6 minutes (6.8 to 5.6 nm) where the energy varies in a 10 dB sinusoidal pattern around 132 dB re 1 μPa^2 s, the second region covers the time interval 6 to 20 minutes (5.6 to 2.7 nm) where the energy varies linearly at -7 dB/nm. The third region covers the time interval 20 to 27 minutes where the U.S.S. Nicholson has made a 90 degree turn (see Figure 10).
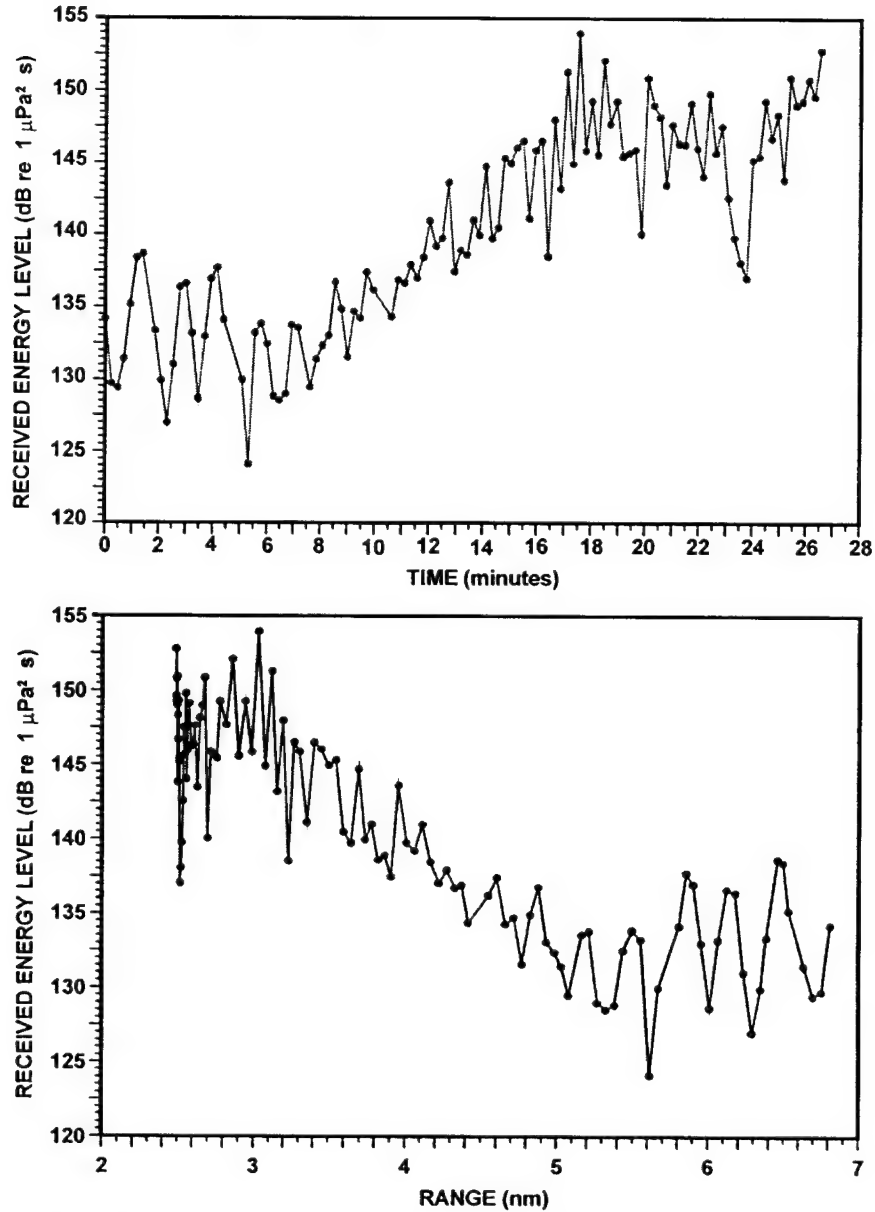
Figure 14: Received energy level for U.S.S. Nicholson SQS-53C LFM signal as a function of time and range to receiver. Start time was 1725 hours (Z) on 14 September 1997.

3.2. TIME-SPREAD MEASUREMENTS

Replica correlation time series of the SQS-53C LFM pulses on VLA channel 1 were calculated by applying an inverse Fourier transform to the normalized frequency domain matched filter output, $\dfrac{\hat{R}(\omega)}{\left|\hat{R}(\omega)\right|}$. Representative replica correlation time series are presented in Figure 15 and Figure 16 which show significant time-spread with 3 or more multipath arrivals. While not visible in these figures, the forward scatter reverberation decay is seen

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to be as much as 10 s. Figure 15 presents 4 sequential LFM pulses and shows the pulse propagation variability over 93 meter spatial scales and 14 second time scales. Figure 16 presents 5 LFM pulses at 5 minute intervals and shows a significant variability in the multipath structure over these time scales.
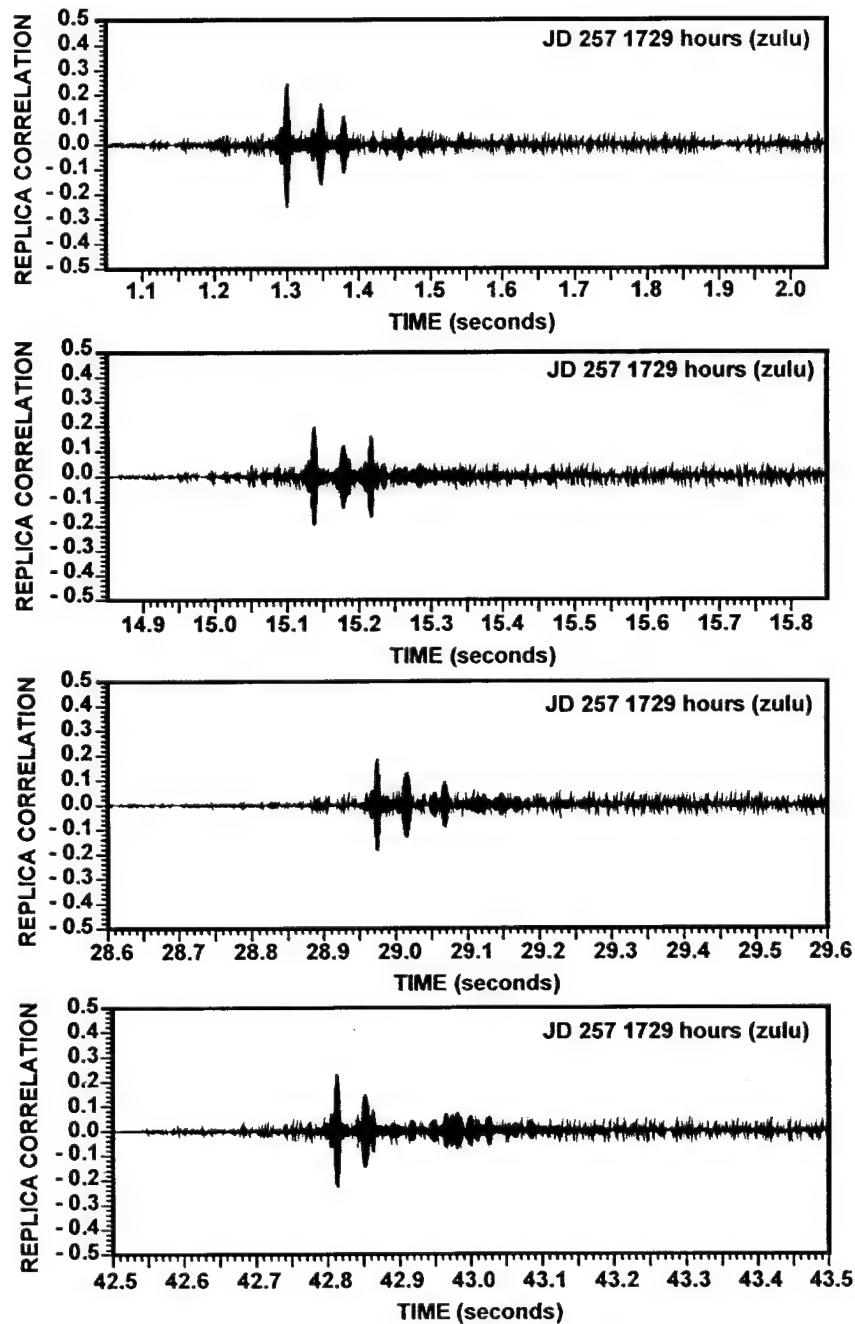

Figure 15: Replica correlation time series for four sequential LFM pulses separated by 14 s. Nominal Range was 5.9 nm.
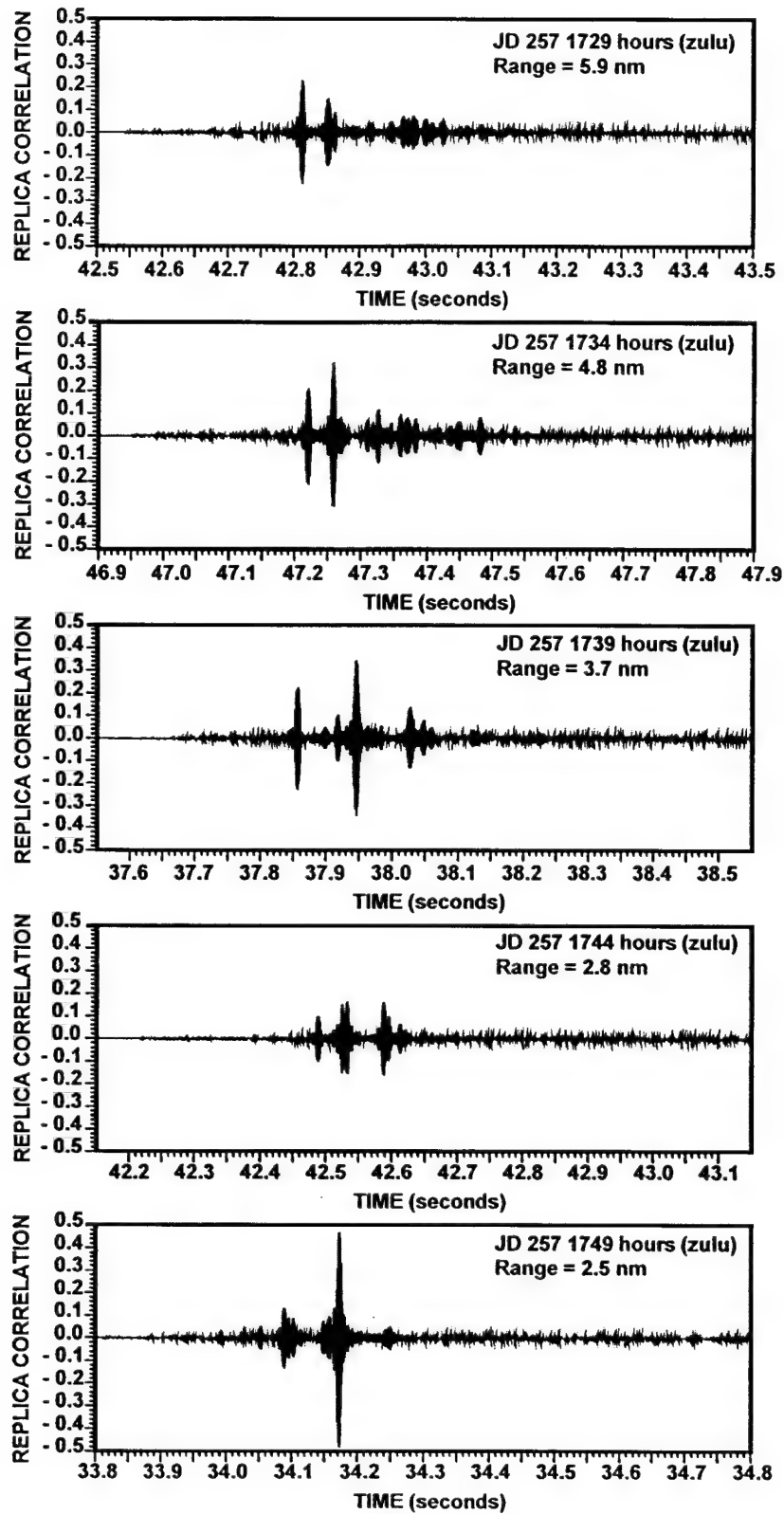
Figure 16: Replica correlation time series for five LFM pulses separated by 5 minutes.

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The peak value of the normalized replica correlation gives an indication of the time-spread losses due to one-way propagation which will influence detection performance. Figure 17 shows the peak value of the replica correlation for each LFM pulse as a function of time and range. The peak correlation values are relatively consistent at a level around 0.25 for ranges from 4 to 7 nm. This low peak correlation value indicates that significant pulse spreading is involved. At closer ranges the peak correlation tends to be higher (as expected), but shows higher fluctuations than found at longer range.
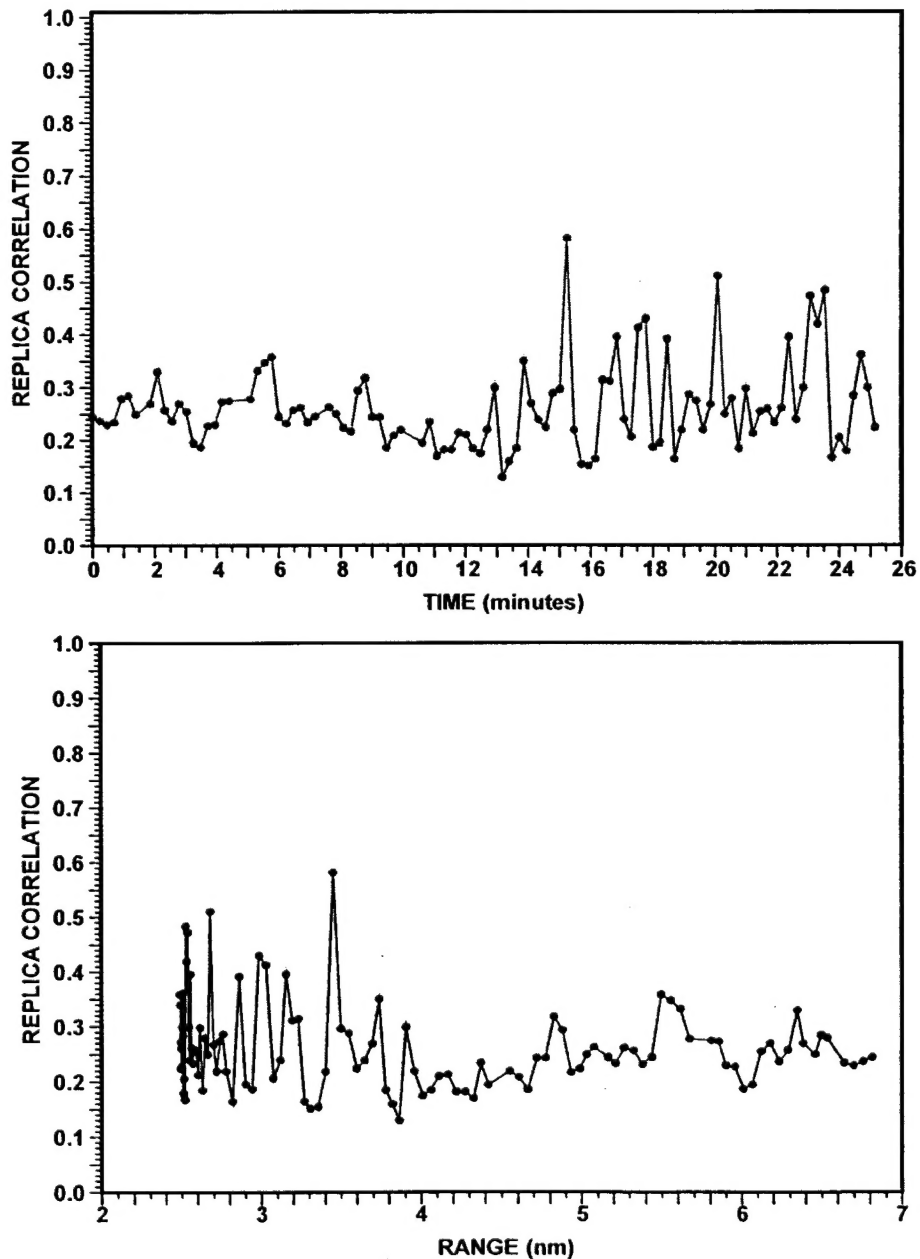

Figure 17: Replica correlation peak values of the LFM pulse as a function of time and range. Start time was 1725 (Z) on 14 September 1997.

4. ACOUSTIC DATA SETS

Acoustic propagation data collected aboard the R/V Gosport were primarily recorded on a TEAC model RX-832 digital data recorder. This 32 channel data recorder has a 12 kHz per channel bandwidth with 16 bit dynamic range. An external GPS derived IRIG-B time code was used by this recorder to time stamp the data. Acoustic data were also recorded on a SONY model PCM 108M digital data recorder. This 8 channel data recorder has a 5 kHz per channel bandwidth with 16 bit dynamic range. An internal clock, synchronized to the GPS time code at the start of the experiment, provided a time stamp for the recorded data. Table 4-1 and Table 4-2 show the times that acoustic data were recorded on the TEAC and SONY data recorders. These raw acoustic data are available to LWAD participants.

DATE JD	DATE	TIME (ZULU)	TAPE ID	COMMENTS
256	9/13/97	22:44 - 23:44	TEAC TL 1	Event 11
256	9/13/97	23:46 - 00:48	TEAC TL 2	Event 11
257	9/14/97	00:51 - 01:41	TEAC TL 3	Event 11
257	9/14/97	04:16 - 04:53	TEAC TL 4	Event 12
257	9/14/97	04:53 - 05:55	TEAC TL 5	Event 12
257	9/14/97	05:56 - 06:58	TEAC TL 6	Event 12
257	9/14/97	17:00 - 17:53	TEAC TL 7	SQS_53C propagation run

Table 4-1: Tape log for the 32 channel TEAC RX-832 recorder showing times data were collected. This is the primary acoustic propagation data record.

DATE JD	DATE	TIME (ZULU)	TAPE ID	COMMENTS
252	9/9/97	18:29 - 20:45	SONY TL 1	ZL TL
252	9/9/97	20:55 - 21:00	SONY TL 2	ZL TL
255	9/12/97	19:58 - 22:28	SONY TL 3	ZLS TL
255	9/12/97	22:28 - 22:45	SONY TL 4	ZLS TL
256	9/13/97	22:44 - 00:48	SONY TL 5	Event 11
256	9/13/97	00:51 - 01:41	SONY TL 6	Event 11
257	9/14/97	04:16 - 06:19	SONY TL 7	Event 12
257	9/14/97	06:20 - 07:00	SONY TL 8	Event 12
257	9/14/97	17:00 - 17:53	SONY TL 9	SQS-53C propagation run

Table 4-2: Tape log for the 8 channel SONY PCM-108M recorder. This is primary data recorder for sonobuoy data at site ZL and ZLS and secondary recorder for VLA data.

5. SUMMARY and CONCLUSIONS

CW transmission loss values at site ZL agree well with previous measurements in the area and with HEP flight SUS measurements made during the SCV 97 experiment, but

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are 5 to 10 dB greater than previous modeling efforts. Additional modeling will be required to resolve this transmission loss discrepancy and to identify potential causes for the relatively high loss.

Received pulse energy levels calculated from the SQS-53C propagation measurements at site ZLS varied from 125 dB re 1 μPa^2 s at 5.8 nm to 155 dB re 1 μPa^2 s at 2.7 nm. The received pulse energy as a function of range appears to separate into two distinct regions. For the ranges between 2.7 and 5.6 nm the received pulse energy as a function of range appears nearly linear with a -7 dB re 1 μPa^2 s per nautical mile slope. For ranges between 5.6 and 6.8 nm the received pulse energy seems to oscillate about a value of 135 dB re 1 μPa^2 s. It is likely that this range effect is due to the occurrence of temporally unresolved multipath components at short range. Final determination will require more additional modeling efforts.

Replica correlation of the SQS-53C propagation data at site ZL show significant time-spread with 3 or more distinct multipath arrivals. The multipath structure is seen to vary a great deal as a function of range/time (the experimental setup did not allow decoupling of range and time). The peak correlation values are seen to be more stable at ranges greater than 4 nm than at closer ranges. This may be due to the signal bandwidth over-resolving the energetically significant multipath components at ranges greater than 4 nm. The peak correlation also indicates that a detection system can expect to see higher echo variability at ranges less than 4 nm, although the echo strength will also be greater.

6. ACKNOWLEDGMENTS

7. REFERENCES

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